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Troy Goodson, Brent Buffington, Yungsun Hahn, Nathan Strange, Sean Wagner, and Mau Wong

Jet Propulsion Laboratory
California Institute of Technology

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Abstract

The Cassini-Huygens mission to Saturn and Titan was launched in 1997. It is an international effort to study the Saturnian system. Cassini-Huygens' interplanetary cruise delivered the spacecraft to Saturn in 2004. It also made use of many propulsive maneuvers, both statistical and deterministic. Maneuver-related analysis and performance for latter half of cruise is reported. The system has performed more accurately than the pre-launch expectations and requirements. Additionally, some maneuvers have already been skipped, saving propellant and flight team effort. Analysis of historical execution error data is presented.

INTRODUCTION

The Cassini-Huygens mission, an international effort to study the Saturnian system, was launched in 1997. Cassini-Huygens' interplanetary cruise, which delivered the spacecraft to Saturn in 2004, made use of one Deep Space Maneuver (DSM) and four gravity assists: two from Venus, one from Earth, and another from Jupiter. It also made use of many propulsive maneuvers, both statistical and deterministic. The trajectory and events of interplanetary cruise are depicted in Figure 4.

Maneuver-related analyses and performance have already been reported for the period from launch through the Earth swingby.[1–3] The remainder of the cruise maneuvers have been executed and are reported herein. The system has continued to perform more accurately than pre-launch expectations and requirements so that some maneuvers have already been skipped, saving propellant and flight team effort.

*Authors are members of the Cassini Navigation Team, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Previously-reported experience ended at TCM-13. The scope of this presentation ends with arrival at Saturn, through TCM-22. These were used for upkeep of the propulsion subsystem, to achieve a suitable swingby at Jupiter, an exciting flyby of Saturn's moon Phoebe, a safe passage between Saturn's F and G rings at arrival, and the appropriate approach geometry for the orbit insertion burn. Arrival at Saturn saw execution of Saturn Orbit Insertion (SOI) and the small execution errors of that maneuver enabled the cancellation of OTM-001, also referred to as SOI Clean-Up (SOI-CU).

Maneuver design and execution errors are summarized in anticipation of annexing more data[4] to produce estimated parameters for a Gates model[5] of execution error ΔV. Estimates of maneuver execution ΔV and so on, are taken from Orbit Determination reconstructions of the trajectory from the Earth swingby to Jupiter and from Jupiter to Saturn.[6,7]

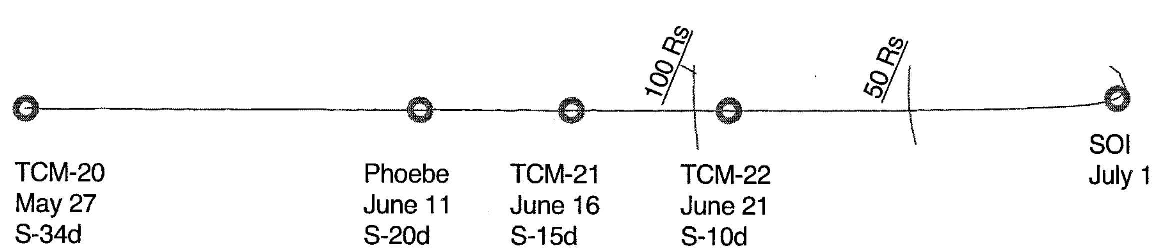
OVERVIEW

Although the Jupiter flyby was essentially the lone trajectory event between the Earth swingby of 1999 and the Phoebe flyby of 2004, there was a relatively high level of planning work on the ground. This is evidenced by the number of updates to the reference trajectory during this period, listed in Table 6. The reference trajectories serve as the source for best estimates of geometry and timing for future events, like a closest-approach to Titan; the source for maneuver-targeting aimpoints; and as the starting point for OD and maneuver statistical analyses.[8]

During the roughly-four-year period between TCM-13 and TCM-20, the requirement to perform a main-engine burn of at least 5 seconds duration and spacing of at least every 400 days became importnat. This requirement ensured Propulsion Module Subsystem (PMS) maintenance. The trajectory 000331 introduced the biases necessary to meet the requirement. TCMs 19a and 19b were not used for PMS maintenance, they were test maneuvers. TCM-19a tested the Reaction Control Subsystem (RCS) command sequence for maneuvers and TCM-19b tested most aspects of the SOI command sequence.

Starting with TCM-20 in May 2004, the trajectory events came relatively quickly. The Phoebe flyby was on 11 June 2004. The ring-plane crossings, SOI, and pericrone were all on 1 July 2004. OTM-001, the clean-up maneuver for SOI, was on 3 July 2004. The Phoebe flyby was designed, in reference trajectory 000331, to produce an altitude at closest-approach of 2,000 km. A trajectory time-line is depicted in Figure 5. B-plane aimpoints for these maneuvers are listed in Table 2 and shown together in Figure 2.

TCM-21 was executed on 16 June 2004, 5 days after the closest approach to Phoebe and 15 days before Saturn periapsis. TCM-21 targeted a specific ring-plane-crossing point that preceded SOI and then a second, descending ring-plane crossing. Both crossings were between Saturn's F and G rings. Careful analysis was made prior to the Ascending Ring-Plane Crossing (ARPC) and Descending Ring-Plane Crossing (DRPC) to ensure the spacecraft would be a safe margin from the known hazards of the F and G ring, less-understood haz-



Rs is short for Saturn Radii, TCM-22 was a contingency maneuver

Figure 1 Trajectory Diagram from TCM-20 to SOI

ards of the Mimas debris field, and possible debris in the orbits of Janus and Epimetheus, referred to as the Janus/Epimetheus Exclusion Zone.[9]

At the last opportunity for a maneuver on approach, TCM-22 was placed. TCM-22 was considered a contingency maneuver. It was not included in the statistical analyses for Navigation to avoid any reliance on the maneuver to meet requirements. It would only be executed if such was required to ensure that spacecraft arrived safely into Saturn-centered orbit and that some degree of the planned tour would be maintained. Fortunately, no such measure was necessary and the maneuver has gone unused.

The boundary between interplanetary cruise and Saturnian tour is occupied by the SOI maneuver. Details of SOI have been previously reported[10,11] but a summary of the maneuver performance is herein. SOI was designed much further in advance than other maneuvers to allow for more extensive testing of the spacecraft-command sequence. The burn used a burn-cutoff algorithm, the Energy Cutoff Burn (ECB) algorithm, that, for testing, was only shared with TCM-19b. Always a positive indication of such performance, the SOI clean-up maneuver, OTM-001, was cancelled without incurring any significant ΔV penalty.

Propulsion Subsystem Flushing

The trajectory segment from Earth to Jupiter was long and much less eventful than prior segments so that PMS maintenance became important. This maintenance primarily consistent of satisfying a requirement for flushing. The requirement is to "perform a burn of at least 5 seconds duration (long enough to clear the wet portion of the propellant lines of the main engine) on any engine that is both wetted and still usable ... as often as required to ensure that the main engines are unfired for no longer than 400 days (note that the last firing must be at least 5 seconds in duration." The concern is that "iron alloys in the bipropellant feed system and REA are attacked by the oxidizer forming ferric nitrate which goes into solution. After a sufficient period of time, the oxidizer becomes saturated with these iron compounds which can subsequently precipitate out in small passageways or as

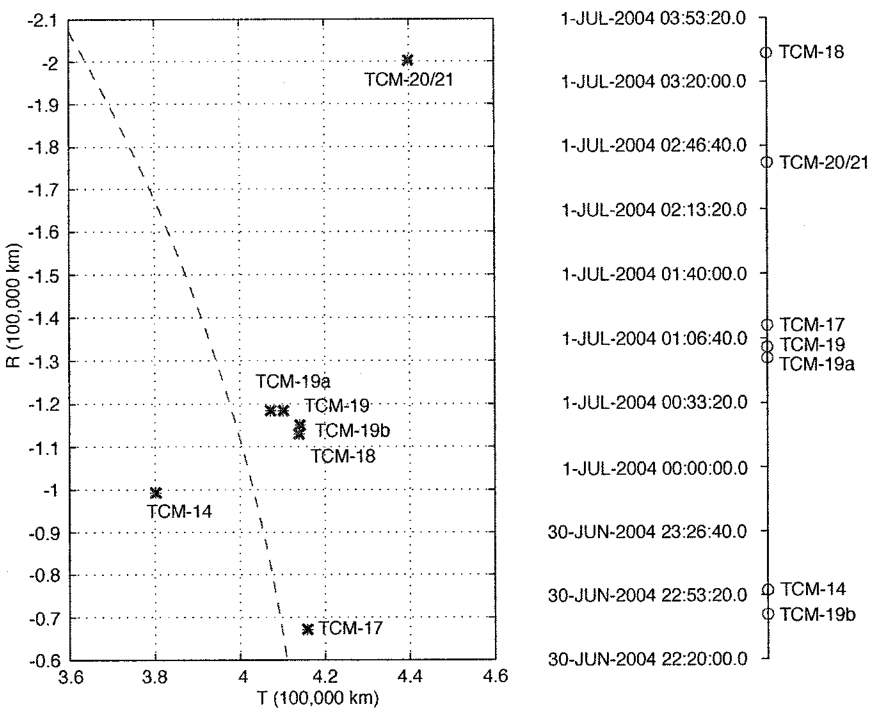


Figure 2 Maneuver targets mapped to Saturn's B-plane, Ecliptic of J2000.0

a result of decreases in oxidizer temperature. The precipitated iron compounds can plug small orifices adversely affecting engine performance."[12]

In planning the maneuvers for this segment, TCM-14, TCM-17, TCM-18, TCM-19, and TCM-20 were selected as flushing maneuvers. In its configuration during that time, the spacecraft would impart about 0.5 m/s ΔV over a 5 second burn and, likewise, this requirement was translated into a minimum ΔV magnitude of 0.5 m/s for these maneuvers. Reference trajectory 000331 was the first to include biases specifically to ensure that these maneuvers would meet or exceed this requirement.[13]

Test Maneuvers

In the latter part of 2002, a new maneuver, TCM-19a, was introduced[14] for the purpose of checking out the capability to perform an RCS maneuver. Without this maneuver, there would not have been an RCS burn between TCM-7, executed in May 1999, and SOI in July 2004. The quickened pace of maneuver execution during the tour made it obvious that the less active period between Jupiter and Saturn was an ideal time to perform such a test. Additionally, the command sequence to be used for RCS maneuvers during tour would be different than the one used previously; notably, all spacecraft turns for such a maneuver would be performed with the Reaction Wheel Assembly (RWA) instead of RCS. In light of that, the TCM-19a ΔV was constrained to be parallel to the direction from Earth to the

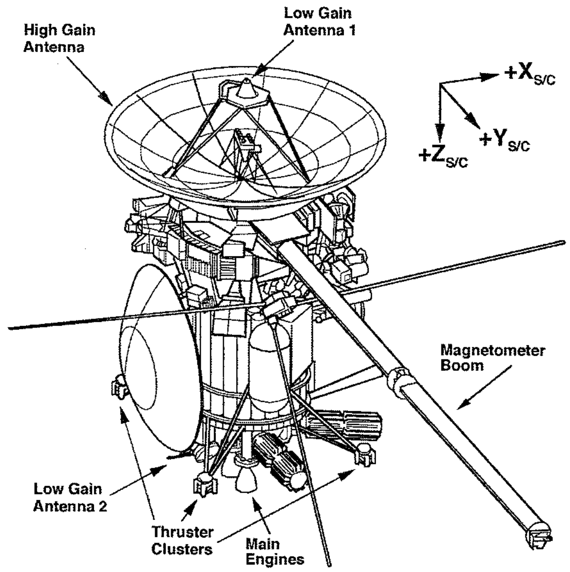


Figure 3 Cassini-Huygens Spacecraft Diagram

spacecraft.* As the spacecraft would be pointed at Earth before the maneuver, this would exercise the RWA system with a large turn angle. The maneuver's design would be fixed — not adjusted with Orbit Determination (OD) estimates — to impart 120 mm/s ΔV, lasting about 3 minutes.[15] TCM-19a was executed September 10, 2003.

Also in late 2002, the test maneuver TCM-19b was proposed. TCM-19b would be an ME maneuver and demonstrate, well in advance of SOI, the same command sequence that would be used for SOI, except for burn ΔV. TCM-19b used SOI's specialized burn-cutoff algorithm and its spacecraft turn rate during the burn execution.[15,16] The ΔV magnitude of TCM-19b was fixed — like TCM-19a, no OD updates — at 2 m/s. The direction of TCM-19b ΔV was not fixed but chosen to ease the redesign of the reference trajectory. The maneuver was executed October 2, 2003, about three weeks after TCM-19a.

These two maneuvers were, for the most part, incorporated into the reference trajectory by removing bias ΔV from TCM-19. TCM-19 would occur before TCM-19a or TCM-19b and, although designed with the latest OD estimates, would include fixed ΔV designs for TCMs 19a and 19b. In this way, the Saturnian aimpoint for TCM-19 would be reached only if all three maneuvers (19, 19a, & 19b) executed without error.

The changes to the approach design[15] in reference trajectory 030201 preserved, as much as possible, reference trajectory 020425 and increased the total approach ΔV by 0.6 m/s (deterministic), with TCM-19 and TCM-20 absorbing most of the added ΔV. TCM-19b's burn direction was chosen to reduce the total ΔV and to have the pre- and post-TCM-19a aimpoints land outside Saturn's impact disk. The TCM-19b Earth-look angle was about

*This was often referred to as the anti-Earth-line direction

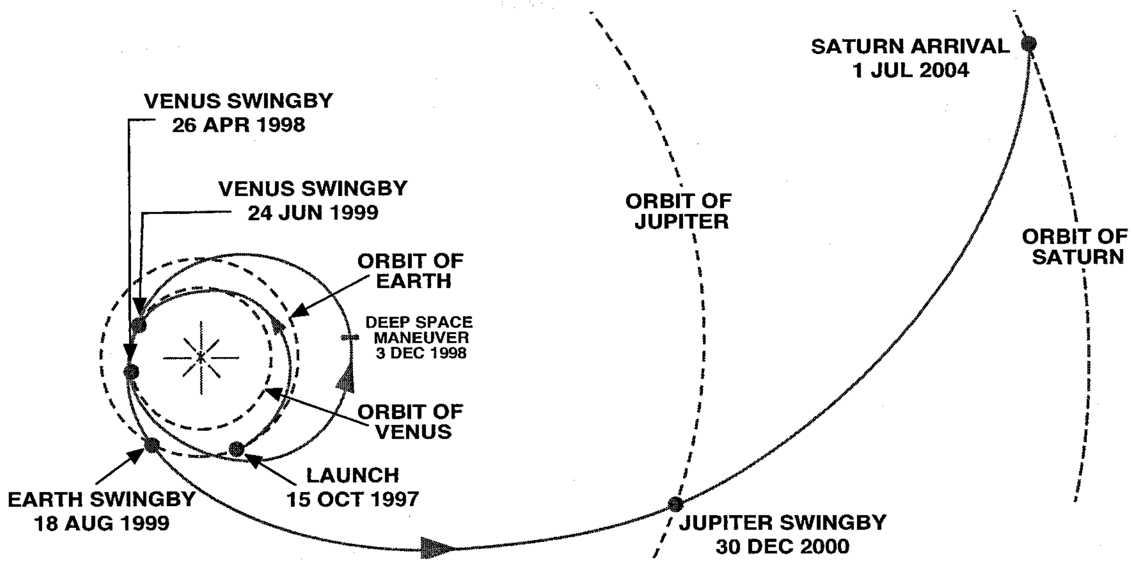


Figure 4 Interplanetary Cruise Trajectory

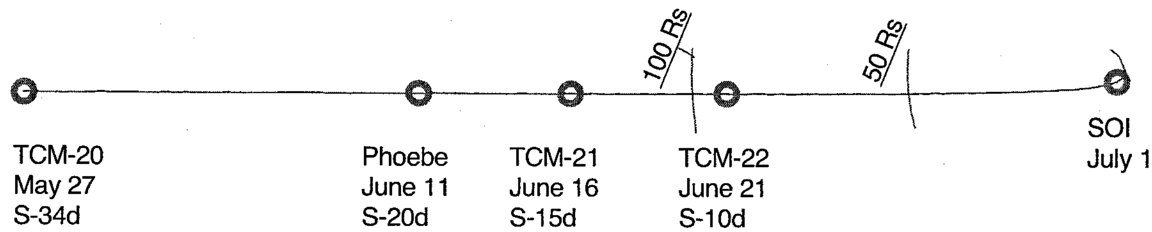
101.4°.

All of the regular TCMs had backup locations. But, it was not obvious whether TCMs 19a and 19b needed to have backup maneuvers. To discover if backup maneuvers for TCM-19a and TCM-19b were needed, several scenarios were simulated for the approach trajectory. Failing to perform either TCM-19a or TCM-19b would have a drastic effect on the maneuvers following TCM-19b. Although TCM-20 would reduce in size, TCM-21 would increase substantially, 20 to 40 m/s, accounting for most of the total approach ΔV penalties. Because TCM-21 was desired to be relatively small (in the couple of m/s range), scheduling a backup maneuver in case TCM-19a or TCM-19b failed became necessary.[15] The backup maneuver for TCM-19a, TCM-19a-BU, was scheduled for 11 September 2003. The backup maneuver for TCM-19b was, effectively, TCM-19c on 9 January 2004. TCM-19c was called the SOI Simulation Contingency maneuver as it primarily provided a contingency opportunity to test SOI capabilities. It also provided an last scheduled opportunity to correct for any ΔV failings of TCM-19a or TCM-19b.

Phoebe Flyby

The trajectory approaching Saturn featured a flyby of the moon Phoebe, targeted by TCM-20. TCM-20 was executed in May 2004, a sizeable ΔV (approx. 35 m/s) that was also chosen to be compatible with the ring-plane crossing, so that it helped set that up as well. The maneuver was incorporated into the Saturn-approach trajectory 000331 when a non-targeted, distant Phoebe flyby was converted into a targeted one, a strategy change that was initiated in June 1999.[17] The maneuver is relatively large because it performs a dog-leg:

one may imagine a straight-line trajectory that represents the path the spacecraft was on before the altitude at Phoebe was lowered and a second straight-line trajectory that extends through both the desired Phoebe aimpoint and the Saturn-ring-plane crossing aimpoint. Essentially, the ΔV of TCM-20 provided the proper kink to connect the two trajectories. An additional kink between Phoebe and the ring-plane crossing might've allowed for a reduction in the total ΔV, but it also would've introduced a non-zero deterministic component to TCM-21 whereas the desire was to minimize the ΔV of TCM-21.[18]



Rs is short for Saturn Radii

Figure 5 Trajectory Diagram from TCM-20 to SOI

As the maneuver that targeted this flyby was so large, there was interest in understanding how the ΔV changed if that maneuver were to be delayed. Assuming that the SOI design would be held fixed, the increase in TCM-20 itself was found to come from the time-to-go penalty (relative to Phoebe), while deterministic components would appear in TCM-21 and OTM-001. (Nominally, they would be the statistical clean-up maneuvers for TCM-20 and SOI, respectively.) The penalties in TCM-20, 21, and OTM-001 were seen grow rapidly with increased delay, while the nominal PRM size was large enough to absorb the variations. While probably not necessary for a three-day delay, it was recommended that TCM-22 be invoked for a delay as long as 5 days. In both cases, TCM-22 would be targeted to the ring-plane crossing, which practically amounts to giving up the Phoebe science completely, as seen by large changes in the flyby conditions.[19]

Saturn Ring-Plane Crossings

The Cassini-Huygens arrival at Saturn was framed by Saturn ring-plane crossings. On approach, there was an ascending ring-plane crossing and on departure, a descending ring-plane crossing. The reference trajectories starting with 030201 were designed with both ring-plane-crossing distances at 158,500 km without a deterministic ΔV at TCM-21. At that distance the crossings were between the F and G rings and avoided debris fields of concern.[20]

The ascending ring-plane crossing was targeted to occur at 00:46 UTC, preceding SOI which commenced 01:12 UTC. The descending ring-plane crossing was planned for 04:34 UTC, after SOI completed. Only the ascending crossing was targeted. The descending crossing was set in the reference trajectory, but perturbed by execution errors, etc., without direct compensation via a maneuver. As maneuvers on approach to Saturn were designed, the characteristics of the descending crossing were carefully monitored and assesed.[21]

The trajectory of the spacecraft was designed to not only avoid the F and G rings, but to also avoid potential debris fields that may exist in the neighborhood of the orbits of Mimas, Janus, and Epimetheus. For both the ascending and descending ring plane crossing trajectories, the spacecraft's predicted 3σ-error corridor neared a possible Janus/Epimetheus debris field by about 150 km, came closest to the F and G rings by around 5500 km and 1000 km, respectively, and passed near a potential Mimas debris field by about 1500 km.[9]

By not targeting the DRPC, there was concern that it might be perturbed to an unfavorable location. While this was carefully monitored and assessed during operations, it was also the subject a study investigating the effects of SOI.[20] In that study, the ECB algorithm was simulated for several burn-delay and burn-interruption cases to understand how those variations affect the radius of the ring-plane-crossing point. The error of concern here was the distance at which the descending ring-plane crossing (DRPC) occurs. This variation in distance was the primary indicator of whether the trajectory would pass too close to any given debris field's exclusion zone. Simulation results showed that all cases crossed beyond the Janus/Epimetheus exclusion zone, but that an increase of 4,000 km occured for most delays that were longer than about 30 minutes and occured sometime in the first 50 minutes of the burn. Such cases would intersect the G-ring and/or Mimas exclusion zones.

Another concern surrounding the ring-plane crossings was that some evidence, perhaps pictures, would indicate that the planned crossing point was not safe. It would've been necessary to adjust the ARPC by retargeting TCM-21. The ARPC radial position was varied from -1000 km to +1000 km away from the reference value of 158,500 km in increments of 250 km. The effects on downstream ΔV's throught the Huygens mission and proximities to rings/debris fields were computed. The variations in TCM-21 size itself were minimal, less than 1 m/s. Most of the downstream ΔV cost would be incurred at OTM-001, whose size would range up to 18 m/s.[22] Going a bit further, to target the ring-plane crossings past the orbit of Mimas would make moot most such concerns but, unfortunately, use almost all of the mission's ΔV margin.[23]

SOI

With a name that describes its purpose, the Saturn Orbit Insertion maneuver was unique in many ways. The timing of this maneuver was critical, as the opportunity to achieve an elliptical orbit around Saturn lasted for only a matter of hours. To increase the probability of performing this maneuver in a timely manner, a second main engine was available to complete the maneuver in the event of an interruption in the prime engine. Yaw steering enhanced this capability by accommodating longer burn interruptions than would have been possible with an inertially-fixed burn direction. Furthermore, rather than centering the burn around periapsis to minimize ΔV cost, SOI was executed approximately 25 minutes after ARPC and ending near pericrone, allowing for greater capability in restarting the burn;

also for science observations closer to Saturn and the inner rings than any time during the tour.

The spacecraft approached Saturn with a V_∞ of 5.2 km/s. SOI, with a cost of 626 m/s, slowed the spacecraft into a Saturn-relative orbit with an orbit period of 116 days (Later, Periapsis-Raise Maneuver (PRM) increased that period to 124 days.)[18]

The burn was controlled by the ECB algorithm which used a criteria of orbital energy for burn cutoff instead of time or ΔV.[10] The ECB algorithm, to be brief, used an on-board, Inertial Vector Propagator[24] (IVP), prediction of spacecraft velocity vs. time to generate an approximation of the change in orbital energy imparted while the burn was in progress. The cut-off criteria was for this approximation of imparted energy to meet a specified value. In this way, if the burn started late or was interrupted for whatever reason, the appropriate change in energy would still be made and the intended orbital period would still be reached.

The same expression used by the on-board algorithm was used on the ground to compute the ΔE_{target}:

$$\Delta E_{target} = \int_{t_o}^{t_f} \vec{V}(\tau) \cdot \vec{a}(\tau) d\tau \tag{1}$$

where t_o is the nominal SOI start time, t_f is the nominal SOI end time, $\vec{V}$ is the velocity-vector from the Cassini-Saturn IVP model, and $\vec{a}$ is the nominal acceleration from the burn-direction IVP model.[25]

Execution of the Deep Space Maneuver had revealed a 0.9° error in pointing Main Engine Assembly A (MEA-A).[2] The pointing bias has been corrected in every main-engine burn since, including TCM-6, via a 7OFFSET command. However, the design of the command sequence and ECB algorithm for SOI required that there be no 7OFFSET rotation and, therefore, no correction to the pointing bias.[26]

In the command sequence, the burn direction is modeled in IVP as a circular orbit around the spacecraft. The angular difference between the two models is shown here in Figure 6. The maximum angular difference during the nominal burn is 0.4°, an indicator of how much this will contribute to the ΔV pointing error.

With the IVP pointing profile, executing the nominal ΔV of 626.35 m/s requires a small, 1.3 m/s ΔV at OTM-1 to achieve the desired orbital period and semimajor axis. Noting changes to other, downstream maneuvers reveals a total cost of 2.66 m/s due to the difference between IVP and DPTRAJ modeling.[26]

The mechanical pointing bias mentioned above is, in magnitude, a 0.9° error. As the size of SOI is 626.35 m/s, such a pointing error would amount to a ΔV of 9.8 m/s. Knowing that SOI magnitude errors scale by 5 when corrected at OTM-1, a 9.8 m/s magnitude error would cost 49 m/s to correct at OTM-1. However, the downstream cost of a pointing error for SOI is actually about the same or less than the pointing error itself, approx. 7 m/s in this case, which is a rather favorable situation and is the motivation for generally ignoring pointing errors in studies of OTM-001.[26]

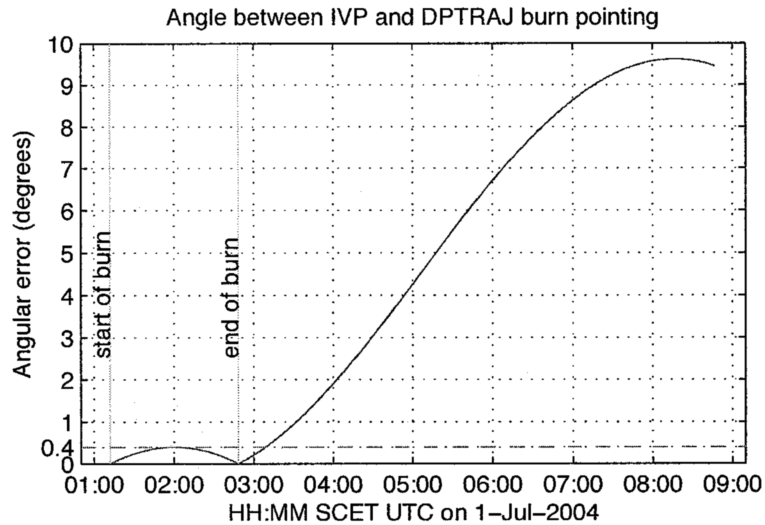


Figure 6 Comparison of IVP and DPTRAJ Pointing for SOI's Burn Vector

MANEUVER EXECUTION

Cassini-Huygens' PMS consists of a bipropellant element, the main engine, for large trajectory corrections and a monopropellant element, the RCS, for small trajectory corrections, attitude control functions, and reaction wheel desaturation. Both are noted on Figure 3. Not shown in the diagram is a clamshell-style cover for the main-engine. The cover is typically deployed (closed) between maneuvers and stowed prior to the maneuver's main command sequence.

Main-engine maneuvers may be either pressure regulated or performed blowdown.[12] Since TCM-13, two of the main engine burns, TCM-20 and SOI, were pressurized and the others were performed in blowdown mode.

The RCS consists of 4 hydrazine thruster clusters — a total of 8 primary and 8 backup thrusters. These small, monopropellant thrusters supply about 0.98 Newtons each when fully pressurized and an I_{sp} of about 195 seconds. They are labeled in Figure 3. The thrusters may be grouped into two sets. The first set faces the +/- $Y_{S/C}$ spacecraft directions; it is used to make balanced turns about the $Z_{S/C}$ axis (roll turns). The other set faces the -$Z_{S/C}$ axis and is used to make unbalanced turns about the $X_{S/C}$ axis (pitch turns) and $Y_{S/C}$ axis (yaw turns).

The RCS has been used for small maneuvers, viz. less than 1 m/s. However, a new "cut-off" criterion for the main engine of 0.4 m/s has recently been adopted for choosing either main engine or RCS for a maneuver; i.e., a maneuver greater than 0.4 m/s would generally be performed on main engine. Lowering the cut-off incurs heavier usage of the bipropellant, but saves monopropellant as that system is the backup for the RWA.

Table 1
EXECUTION ERROR MODEL (1-σ)

		MEA	RCS
Magnitude	Proportional (%)	0.2	2.0
	Fixed (m/s)	0.01	0.0035
Pointing	Proportional (mrad)	3.5	12
	Fixed (m/s)	0.0175	0.0035

Execution errors are modeled using the Gates model.[5] The Gates model accounts for four independent error sources, fixed and proportional magnitude errors (σ_1,σ_2) and fixed and proportional pointing errors (σ_3,σ_4). Each parameter represents the standard deviation for that error source and each error source is assumed to have a zero mean. So,

$$N(0,\sigma_1^2)\mathbf{u}_1+N(0,\sigma_2^2)|\mathbf{\Delta}V|\mathbf{u}_1+N(0,\sigma_3^2)\mathbf{u}_2+N(0,\sigma_3^2)\mathbf{u}_3+N(0,\sigma_4^2)|\mathbf{\Delta}V|\mathbf{u}_2+N(0,\sigma_4^2)|\mathbf{\Delta}V|\mathbf{u}_3 \quad (2)$$

expresses an execution error where $N(0,\sigma^2)$ is one sample from a Normal distribution, $\mathbf{u}_1$ is parallel to ΔV, and $\mathbf{u}_2$ and $\mathbf{u}_3$ are any pair of vectors both perpendicular to $\mathbf{u}_1$ and each other. Note the implicit assumption that pointing errors may occur in any direction perpendicular to $\mathbf{u}_1$ with equal probability.

The maneuvers since TCM-13 used the updated execution error model, listed in Table 1. This model was prepared prelaunch and partially updated with inflight data.[2]

One may compute execution errors by simply subtracting the expected from the actual ΔV, but most of the insight into the source of the error comes after judiciously choosing a coordinate system to represent it with. Each maneuver ΔV is in a different inertial direction, but is controlled by spacecraft on-board systems, the accelerometer and attitude control system. It makes sense, then, to use a body-fixed coordinate system instead of an inertial system when analyzing the errors. A coordinate system definition, referred to as spacecraft coordinates $X_{S/C}$, $Y_{S/C}$ and $Z_{S/C}$, already exists for Cassini and is denoted in Figure 3. The $Z_{S/C}$ axis points from the high-gain antenna to the main engine, the $Y_{S/C}$ axis points away from the probe, and the $X_{S/C}$ axis completes the right-handed system. However, a coordinate system with an axis parallel to the commanded ΔV is preferred. A reasonable choice is the Thrust Vector Control (TVC) coordinate system which has Z_{TVC} parallel to the commanded ΔV. In this way, the plane perpendicular to Z_{TVC} is the pointing plane, the plane whose normal vector is the commanded ΔV. Also, X_{TVC} is parallel to the projection of $X_{S/C}$ into the pointing plane, and Y_{TVC} completes the right-handed system.

Table 2
MANEUVER TARGETING DATA

	OD	**B** · **R** km	**B** · **T** km	TCA ET	Target
TCM-1	LP15D	-1910.705	12301.850	26-APR-1998 13:45:49	Venus
TCM-2	V1M69D	-1910.705	12301.850	26-APR-1998 13:45:49	Venus
DSM	V1P87D	3269.45	-9774.91	24-JUN-1999 21:53:55	Venus
TCM-6	V2M148D	1121120	-1978790	18-AUG-1999 17:05:43	Earth
TCM-7	V2M48D	160000	21210	18-AUG-1999 03:43:26	Earth
TCM-9	EM52D	14400	57510	18-AUG-1999 03:29:55	Earth
TCM-10	EM36D	2400	57510	18-AUG-1999 03:30:07	Earth
TCM-11	EM22D	6960	10390	18-AUG-1999 03:29:42	Earth
TCM-12	EM11D	164	8960	18-AUG-1999 03:29:29	Earth
TCM-13	EP6D	130523	10898129	30-DEC-2000 10:08:13	Jupiter
TCM-14	JM207D	123623	10897196	30-DEC-2000 10:04:43	Jupiter
TCM-17	JP30D	-55992	352629	1-JUL-2004 01:13:40	Saturn
TCM-18	SM828D	-113061	414551	1-JUL-2004 03:35:07	Saturn
TCM-19	SM433D	21013	426496	1-JUL-2004 01:02:06	Saturn
TCM-19a	SM307D	fixed ΔV			
TCM-19b	SM290D	fixed ΔV			
TCM-20	040525_00Sa	-873.69	1920.63	11-JUN-2004 19:34:41	Phoebe
TCM-21	040615_00Sa	R=158,500 km	δ = 0°	θ=157.8° | t=00:47:38	Saturn

TCM-21: R is Radius, δ is dec., θ is right-ascension and time is t HH:MM:SS on 1-JUL-2004.

Table 3
MANEUVER DESIGN CHARACTERISTICS

	Maneuver Epoch (UTC-SCET)*	ΔV (m/s)	Roll (deg)	Yaw (deg)
TCM-1	9-Nov-1997 20:00	2.746	-35.77	-70.64
TCM-2	25-Feb-1998 20:00	0.185	117.7	-160.6
DSM	3-Dec-1998 06:00	450.0	-170.7	-89.13
TCM-6	4-Feb-1999 20:00	11.55	-18.97	-10.71
TCM-7	18-May-1999 17:00	0.2386	-163.6	-110.1
TCM-9	6-Jul-1999 17:00	43.54	-79.33	-115.3
TCM-10	19-Jul-1999 16:00	5.133	-80.74	-93.29
TCM-11	2-Aug-1999 21:30	36.31	-171.7	-64.86
TCM-12	11-Aug-1999 15:30	12.26	-84.76	-88.37
TCM-13	31-Aug-1999 16:00	6.710	8.63	-83.19
TCM-14	14-Jun-2000 17:00	0.5546	-57.49	-142.49
TCM-17	28-Feb-2001 17:30	0.512	-97.40	-45.16
TCM-18	3-Apr-2002 18:00	0.9007	8.210	-100.78
TCM-19	1-May-2003 20:00	1.598	174.26	-140.23
TCM-19a	10-Sep-2003 20:00	0.120	67.48	180.00
TCM-19b	2-Oct-2003 04:00	2.00	-79.24	-102.17
TCM-20	27-May-2004 22:26	34.73	60.84	-67.79
TCM-21	16-Jun-2004 21:07	3.705	160.20	-11.21

Table 4
MAGNITUDE AND POINTING ERRORS

	Magnitude			Pointing		
	Design ΔV +Events* (m/s)	Mag. Error (mm/s)	1-σ Mag. Uncert. (mm/s)	X_{TVC} Error (mm/s)	Y_{TVC} Error (mm/s)	1-σ Pointing Uncertainty† (mm/s)
TCM-2	0.19	-6.28	0.16	-1.15	-0.17	0.45 × 0.07, 30.0°
DSM	449.97	262.79	0.38	123.56	638.07	6.12 × 0.12, 89.1°
TCM-6	11.56	-9.93	1.16	12.18	2.22	5.16 × 0.11, 113.6°
TCM-7	0.24	-4.89	0.63	-4.66	-7.38	1.92 × 0.12, 92.4°
TCM-9	43.55	-51.97	15.33	36.09	77.27	6.66 × 0.16, 8.7°
TCM-10	5.14	-1.89	3.83	0.08	10.27	0.48 × 0.05, 44.9°
TCM-11	36.32	-21.76	1.81	16.57	63.01	4.52 × 0.07, 85.6°
TCM-12	12.26	-9.34	3.40	-10.64	16.49	0.76 × 0.12, 83.7°
TCM-13	6.72	-12.37	1.85	-7.77	31.82	5.12 × 0.05, 88.1°
TCM-14	0.55	-9.93	2.20	2.24	6.79	2.88 × 0.22, 37.8°
TCM-17	0.54	-2.67	8.23	-13.18	6.50	10.58 × 6.08, 29.7°
TCM-18	0.91	-3.43	3.25	-0.29	1.84	2.89 × 0.45, 92.3°
TCM-19	1.60	4.28	2.89	-6.64	-6.32	4.62 × 3.00, 115.7°
TCM-19a	0.12	2.24	0.14	-2.30	0.99	3.81 × 3.70, 82.8°
TCM-19b	2.00	22.19	4.18	25.19	22.87	5.09 × 0.75, 91.3°
TCM-20	34.73	-24.90	1.88	-32.07	59.12	2.14 × 0.67, 100.3°
TCM-21	3.71	-14.27	0.48	3.85	12.18	2.35 × 2.14, 107.1°

MANEUVER EXPERIENCE

After Trajectory Correction Maneuver (TCM)-2, two flight software corrections were made, both relating to the accelerometer. The accelerometer scale factor was in error by 1%, biasing the system to overburn by that amount. The other correction was one made to the algorithm which compensates for the misalignment between the accelerometer mounting and the thrust vector. This potentially reduced burn magnitude error by as much as 0.8%. These two corrections clearly contributed to the excellent magnitude errors discussed below.

After DSM, the main-engine pointing bias was observed and corrected by altering the spacecraft command sequence.[2] The correction, about 0.9°, appears to be compensating for a discrepancy between the direction that the flight software things that the engine is pointed, partly tied up in modeling of the gimbal actuators, vs. the direction in which it really is.

After TCM-13, the updated execution-error model (Table 1) went into effect. While this did not improve the accuracy of maneuvers, it improved the capability to predict maneuver

*The ΔV magnitude includes the design ΔV (burn and turns) plus all ΔV events related to the maneuver (e.g., deadband tightening, Reaction Wheel Assembly (RWA) / RCS transitions, Earth/Sun pointing, etc.).

†1-σ pointing uncertainty numbers are 1-σ ellipse dimensions (semi-major axis X semi-minor axis) with orientation angle (relative to pointing plane X_{TVC} axis).

statistics.

TCM-14

TCM-14 was primarily a statistical maneuver. The aimpoint for TCM-14 was changed from those in reference trajectory 981218[27] to those in trajectory 000331 to lower the altitude from 52,000 km to 2,000 km for the Phoebe flyby scheduled in 2004 and to introduce the biases for satisfying the flushing requirement. TCM-14 grew large enough to satisfy the requirement almost entirely on the basis of the Phoebe-related changes.

This was to be the penultimate Jupiter-approach maneuver; however, the ensuing cancellation of TCM-15 made it the final approach maneuver. Before the Phoebe-related changes, TCM-14 did not have a deterministic component.[2] The combination of a deterministic component to target Phoebe and its necessity to the flushing requirement, it could not be part of any cancellation discussion.

On the other hand, with less than a year (259 days) between TCM-14 and TCM-17, TCM-15 and TCM-16 could both be considered for cancellation as they were purely statistical clean-up maneuvers. In fact, the decision to cancel TCM-16 was made during development of reference trajectory 000331, from which the aimpoint for TCM-14 was taken.

TCM-14 develoopment began around May 11, 2000. The maneuver development process included a strategy meeting, a kick-off meeting, testing of the sequence in Integrated Test Lab (ITL), followed by an implementation meeting, and an approval meeting. The maenuver was approved on June 12, uplinked the next day and executed on June 14.

TCM-15 & TCM-16

TCM-15 would've been 11 Oct 2000 with TCM-16 as its backup. TCM-16 would've been executed 7 Dec 2000 with a backup location 21 Dec 2000.[27] In light of the superb execution-error performance of this spacecraft; the fact that the Jupiter flyby was very distant, about 10 million km; and that there wasn't any requirement for a highly accurate delivery to Jupiter; it was clear that TCM-16 was not necessary and was cancelled.

TCM-15 was cancelled after the reconstruction of TCM-14 showed that there had been no serious error and that the delivery to Jupiter was reasonable close to the prediction.

TCM-17

TCM-17 was the first maneuver after the Jupiter swingby. The trajectory was designed so as to bias TCM-17 above 0.5 m/s; in fact, a deterministic bias of that size was assigned to TCM-17. The statistical part of TCM-17, obtained by subtracting the deterministic bias from the designed ΔV, had a magnitude of only about 0.1 m/s. In any case, it was the smallest main-engine maneuver that had been executed by that time.

TCM-14 was 259 days before TCM-17 so the flushing requirement was met. Had the maneuver design been short of 0.5 m/s, the requirement could still have been met if the maneuver were delayed until about mid-July 2001 or an additional bias were introduced which would've been removed again by TCM-18.

TCM-17 develoopment began around late January 2001. The maenuver was approved on February 22, 2001, uplinked the next day and executed on February 28, 2001.

TCM-18

With TCM-18, the ground system started practicing the maneuver-design process for the tour. During the tour, less time would be available for this process, so meetings needed to be reorganized and reduced, much as the overall maneuver-design procedure would have to be. Development began in early March 2002. The maneuver was approved on 29 March 2002 and executed 3 Apr 2002.

Development work on TCM-18 began in late February 2002. The maneuver was approved on 29 March 2002 and executed on 3 April 2002.

TCM-19

TCM-19 was, again, a biased for the flushing requirement. The design, however, was also influenced by changes to the downstream Phoebe flyby and the designed ΔV rose to about 1.6 m/s. However, it was also used to demonstrate certain SOI activities and prevent them from being first-time activities at SOI. For example, the timing of oxidizer-valve heater on/off timing and Main Engine Assembly (MEA)-cover deployment. Backup location was six days later (almost exactly).

Development on TCM-19 began in April 2003. The maneuver was approved on 30 April 2003 and executed[28] 1 May 2003.

TCM-19a

TCM-19a was an RCS maneuver demo. There hadn't been an RCS maneuver since TCM-7 and it was clear that all maneuvers prior to SOI would be on MEA. This demo was proposed so that the first RCS maneuver in over a year would not occur during the tour, when there would be little time to recover from an anomaly.

Work begain on TCM-19a as early as October 2002, when it was proposed. The maneuver was approved 9 September 2003 and executed 10 September 2003. TCM-19a was implemented by lifting the ΔV designed directly from reference trajectory 030201 and passing it through the usual design software without any alteration for new OD results. The designed ΔV direction was parallel to the Earth-Spacecraft direction with a magnitude of 0.120 m/s.[15] As TCM-19a used the RWA for turns, there would no turn ΔV and, so, no need to decompose the total ΔV into turn and burns. Using the usual design software also made verification of the predicted B-plane delivery easier — in other maneuvers, one would simply verify that requested target was properly searched-in and met, but TCM-19a was not updated to match the reference trajectory's B-plane target, so the predicted B-plane delivery had to be compared to what was read from the reference trajectory.

TCM-19b

TCM-19b used the energy-based termination algorithm[10] and yaw steering[16] in order to demonstrate these techniques before SOI. Like TCM-19a, the design ΔV was lifted from reference trajectory 030201.[15]

Implementing TCM-19b had similarities with TCM-19a. However, TCM-19b was an ME maneuver, requiring the decomposition of total ΔV into turn ΔV and burn ΔV. Furthermore, The burn ΔV vector had to be translated into the command parameters for the SOI's ECB algorithm.[16,25]

Work begain on TCM-19a as early as October 2002, when it was proposed. The maneuver was approved on 24 September 2003 and executed 2 October 2003. Execution of TCMs 19a and 19b were favorable enough to cancel TCM-19c.

TCM-20

TCM-20's primary purpose was to target the Phoebe flyby at an altitude of about 2,000 km.[29] However, the maneuver had a host of important secondary objectives. It was the first fully pressurized and regulated burn in over 4 years (re DSM) and the largest ΔV since TCM-11. The Low-Gain Antenna 2 (LGA-2) was used while the spacecraft was off Earth-point to provide a signal to the Radio-Science Receiver (RSR) to track Doppler shift during the burn. It was the first use of LGA-2 since the Earth swingby. The technique had not been used on Cassini-Huygens before but would be implemented for SOI to avoid a loss of communication with the spacecraft during that crucial event.

Designs for TCM-20 with in-flight OD estimates began around late February 2004. The final design was made on 25 May 2004, approved the same day, and executed on 27 May 2004.

TCM-20's execution went wonderfully well and provided a fruitful flyby of Phoebe. OD reconstruction estimated the actual flyby altitude at 2,071 km and the first direct determination of Phoebe's GM.[7,30]

TCM-21

TCM-21 was the last maneuver before arrival at Saturn. The encounter with Saturn was different from every previous encounter in almost every way. From a maneuver analyst's perspective, one of the top differences was in its targets. Every prior maneuver had used a B-plane target, but TCM-21 targeted Saturn-relative radius and angles of declination and right ascension relative to Saturn Equator of Date. As such the effects of delays and target adjustments were studied.[22,23,31]

Targets were taken from reference trajectory 030201, which had been designed to pass safely between Saturn's F and G rings during both the ARPC and DRPC.[9] As discussed above, TCM-21 only targeted the ARPC, leaving the DRPC to vary according the incoming asymptote and downstream trajectory perturbations. As a result the DRPC had larger variations, although statistics for both were frequently updated and monitored.

Plots depicting the ring-plane-crossing geometry were produced regularly.[21] Figure 7 shows the ARPC including the effects of TCM-21, based on the OD data at the time of designing TCM-21. Likewise, Figure 8 depicts the result for the DRPC. Table 5 summarizes the pertinent charateristics of the ring-plane crossings for the trajectory before TCM-21 was executed, the trajectory with the TCM-21 nominal design, and the OD reconstructed trajectory. Note that, before TCM-21 was executed, the ARPC would've been at 157,488 km, about 1,000 km too close to Saturn and the distance to the Janus/Epimetheus Exclusion Zone would've been less than half the planned value.

Table 5 also shows that, even with the nominal TCM-21 design, the DRPC doesn't achieve the desired distance of 158,500 km, as it is not a target parameter. However, the nominal distance is only 60 km closer to Saturn and the reconstructed value is only 276 km too far from Saturn. Both of these produced acceptable distances from the exclusion zones.

TCM-22

The last approach maneuver, TCM-22, was scheduled for 21 June 2004 20:52 UTC SCET, SOI minus 10 days. TCM-22 wa a contingency maneuver; there was no deterministic component nor was it modeled in Navigation's statistical maneuver analysis. Its placement was a compromise between having adequate time to respond to an anomaly and having enough time-to-go to keep the required ΔV small. If invoked, TCM-22 would've re-targeted the ARPC.[18] With the successful execution of TCM-21, there was no need for TCM-22; it was cancelled.

Table 5
RING-PLANE CROSSING STATISTICS

	ARPC			DRPC	
case	OD	w/TCM-21	OD Recon.	w/TCM-21	OD Recon.
dist	157,488	158,500	158,529	158,540	158,776
F ring	5055	5426	5434	5629	5701
J/E zone	235	542	550	607	678
G ring	1368	1112	1102	1156	1089
Mimas field	1632	1432	1425	1604	1542

distances are given in km, the "OD" column reflects the trajectory without TCM-21

Table 6
REFERENCE TRAJECTORY HISTORY

Name	Release	Design	Comments
000331	April 3, 2000	n/a	flushing mvrs, Phoebe alt., RPC incl., no SOI
000728	July 31, 2000	n/a	update with Jupiter reconstruction
010423	May 2, 2001	n/a	update TCMs 18, 19
010823	August 27, 2001	T2001-01	preliminary Huygens mission redesign
020425	May 10, 2002	T2002-01	Huygens mission redesign
030201	January 30, 2003	T2003-01	add TCMs 19a,b; RPC upd., Huygens upd.
040506	May 4, 2004	T2004-01	new ephems, tour upd., Huygens upd.
040513	May 13, 2004	T2004-01	SOI model updated
040622	June 22, 2004	T2004-02	updated satellite ephem. and tour aimpoints

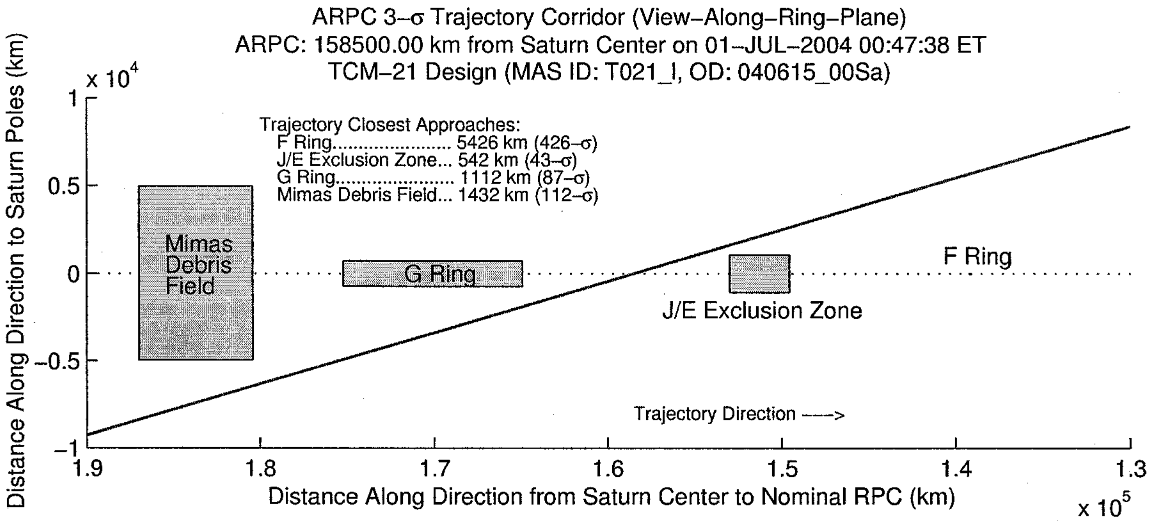


Figure 7 Diagram of the Ascending Ring Plane Crossing Predicted with TCM-21 Design

SOI & OTM-001

The command sequence for SOI completed smoothly and SOI was executed with any burn delays or interruptions. Although sufficient for trajectory and maneuver design, the polynominal-based models available in DPTRAJ for thrust, mass flow rate, acceleration vector right ascension, and declination were not appropriate to represent SOI for the OD reconstruction. However, the data acquired before, after, and during SOI using the RSR at the DSN station was quite good. It allowed for a precise determination of the burn start and end times and enabled a better estimate of SOI by reducing the corrupting effects of pre- and post-burn turns. The model used indicated the ΔV at 626.8 m/s, a duration of 5780.5 seconds, a mass decrement of 841.5 kg, and an 443.1 N average force.[7] Perhaps the most appropriate way to evaluate the performance of SOI is to look at the design of the SOI CU maneuver (OTM-001).

OTM-001 was scheduled for 3 July 2004, two days after SOI, which placed it, somewhat remarkably, at a true anomaly of 159°. The targeting strategy for OTM-001 was unique; it would only correct the orbital period and inclincation in Saturn Equator of Date. The remaining degree of freedom would be used to minimize the ΔV magnitude.[32] This is sometimes referred to as a minimum-norm solution or a critical-plane solution.

A prior study had shown that as long as OTM-001 was 2 m/s or less, it could be cancelled without issue for the remainder of the tour. In some cases, a gain in total ΔV was seen.[33] As it happened, the OTM-001 design on 2 July 2004 with OD delivery 040702c_00Sa was 1.924 m/s ΔV. The errors to be corrected were a 0.4 day too-short orbital period and a

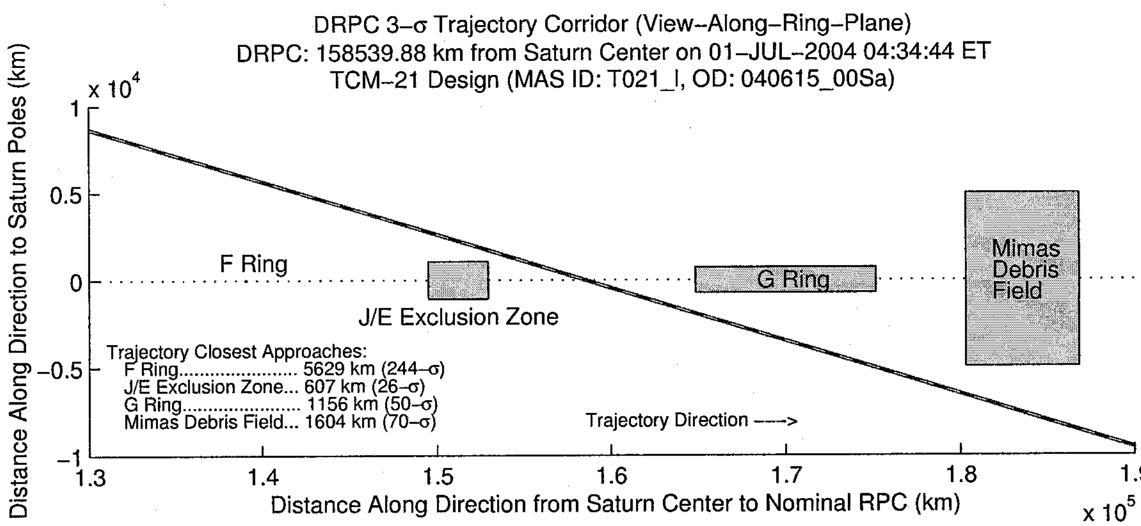


Figure 8 Diagram of the Descending Ring Plane Crossing Predicted with TCM-21 Design

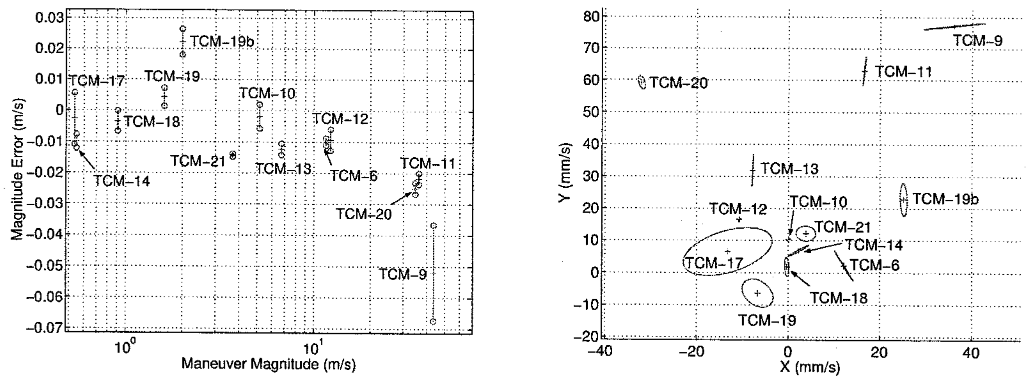
0.02° too-low inclination in Saturn Equator of Date. Using the slightly-later OD delivery 04072d_00Sa showed slightly different errors to be corrected and the ΔV rose to 2.055 m/s.

A brief study verifyied that only slight errors in pointing to Saturn or Titan would be incurred between OTM-001's and OTM-002's (PRM) execution dates if OTM-001 were canceled. Another brief study indicated that the ΔV penalty, through the Titan-4 encounter, of skipping OTM-001 was about the same as the magnitude of OTM-001, about 2 m/s. So, instead of the apparent saving of 2 m/s, there would be an overall cost of 2 m/s which would be fairly evenly split between the post-Titan-a maneuver (a.k.a. Probe-targeting maneuver, PTM) and the post-Titan-c maneuver (OTM-011). With these results in hand, OTM-001 was cancelled.

EXECTION-ERROR ANALYSIS

In the interest of monitoring and keeping statistics on maneuver execution errors, in addition to preparing for the next update to the execution error model, the estimated maneuver ΔV results have been compared to the expected (predicted) maneuver ΔV. The differences between these two represent the execution errors. Just as the model has separate components for magnitude and pointing for both main-engine and RCS burns, the data has been been plotted in these categories.

Figures 9a and 9b show the magnitude and pointing errors for the main-engine maneuvers. The data shown here includes past maneuvers in the interest of observing trends. Not



(a) Magnitude Errors

(b) Pointing Errors

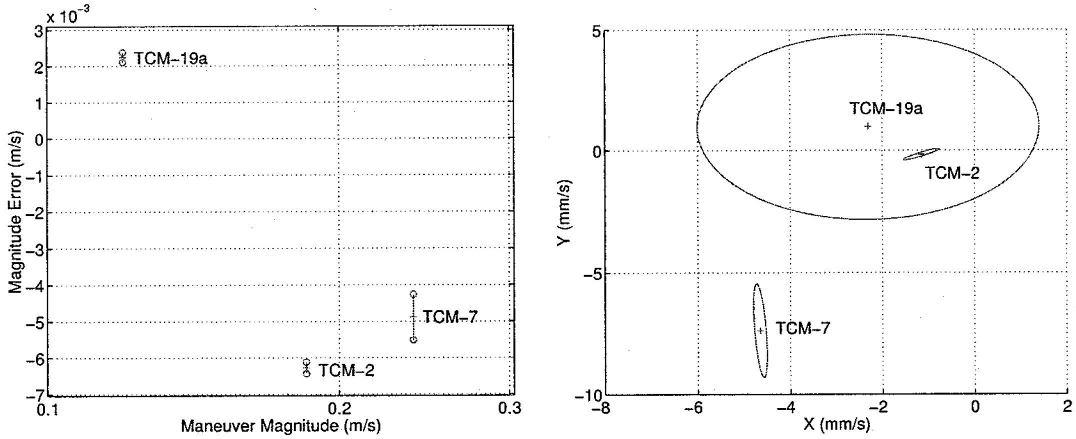
Figure 9 Main-Engine Magnitude and Pointing Execution Errors

shown in the plot is DSM, which is exclusively associated with TCMs 19 and 19b as the only overburn estimates in the list. Investigation is ongoing to determine what aspects of these maneuvers might set them apart; perhaps they should not be included in the analysis to update the execution-error model. In the remaining maneuvers, there appears at least a fixed bias for underburns. Also, since the underburns are more pronounced for larger maneuvers, there is reason to suspect that a proportional bias is also present.

It is more difficult to visually interpret the pointing errors, seen in Figure 9b — again, DSM is excluded from the plot. Pointing errors are already two-dimensional, making it very difficult to depict any correlation between maneuver magnitude and pointing error. Nonetheless, all maneuvers except TCM-19 have positive ΔV pointing error along the Y_{TVC} axis. Careful examination also reveals that pointing errors also tend to increase with increasing maneuver magnitude. A notable oddity is the pointing-error estimate for TCM-20, whose X_{TVC} component is far more negative than other maneuvers, including its near-twin, TCM-11. In fact, excluding TCM-20, one is attracted to the observation that the pointing errors increase in both X_{TVC} and Y_{TVC} components in correlation with maneuver magnitude. Like the magnitude errors, the pointing errors seem to have both fixed and proportional biases present.

Figures 10a and 10b show the magnitude and pointing errors for the RCS maneuvers. Unfortunately, there are only three such maneuvers throughout the interplanetary cruise. The magnitudes of the three maneuvers aren't substantially different: 0.12 m/s, 0.19 m/s, and 0.24 m/s. The magnitude errors, however, show TCM-2 and TCM-7 with very similar underburn estimates, but TCM-19a shows an overburn. While TCM-19a did have some clear differences in its command sequence vs. TCM-2 or TCM-7, but it remains to be seen that this translates into the observed ΔV difference.

The pointing errors for the RCS maneuvers are shown in Figure 10b. In this case, it's even clearer that the three data points are insufficient for a meaningful discussion.



(a) Magnitude Errors

(b) Pointing Errors

Figure 10 RCS Magnitude and Pointing Execution Errors

CLOSING

Experience with the Cassini-Huygens spacecraft has been very successful and should help enable exciting science investigations of the Saturn planetary system. The collection and analysis of maneuver execution-error data has already once borne fruit as an update to the execution-error model, although only the main-engine proportional components really benefited. It seems clear from the data set so far, that the next update will be able to produce meaningful estimates of the fixed components as well. Maneuver ΔV performance thus far has been in the nominal range, and the team fully expects mission success to follow.

APPENDIX: B-PLANE DESCRIPTION

Planet or satellite targeting is described in aiming plane coordinates referred to as *B-plane* coordinates[34] (Fig. 11). The B-plane is a plane passing through the body center and perpendicular to the asymptote of the incoming trajectory (assuming 2 body conic motion). The "B-vector", **B**, is a vector in that plane, from body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the body had no mass and did not deflect the flight path. Coordinates are defined along three orthogonal unit vectors, **S**, **T**, and **R** with the system origin at the body center. The **S** vector is parallel to the spacecraft V_∞vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). **T** is parallel to a convenient reference plane, and **R** completes an orthogonal triad with **S** and **T**. The reference plane for the **T** vector is generally the ecliptic plane (EMO2000). For Titan equator of date, the reference plane is in Titan's equatorial plane at the given epoch. With **S**, **T**, and **R** thus defined, a target point can be described in terms of the B-vector dotted into the **R** and **T** vectors ($\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$), or as the magnitude of **B** and the angle ϕ clockwise from **T** to **B**.

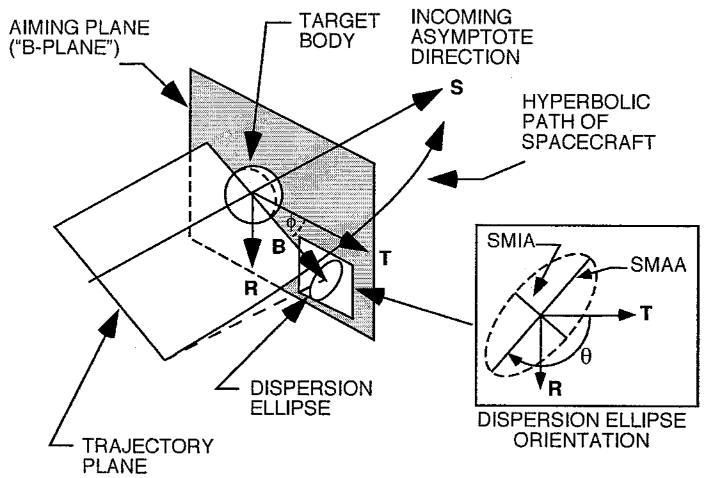


Figure 11 B-Plane Coordinate System.

Trajectory errors in the B-plane are often characterized by a one-σ dispersion ellipse, shown in Fig. 11. SMAA and SMIA denote the semi-major and semi-minor axes of the ellipse; θ is the angle measured clockwise from the **T** axis to SMAA. The dispersion normal to the B-plane is typically given as a one-σ time-of-flight error, where time-of-flight specifies what the time to swingby (periapsis) would be from some given epoch if the magnitude of the B-vector were zero. Alternatively, this dispersion is sometimes given as a one-σ distance error along the **S** direction, numerically equal to the time-of-flight error multiplied by the magnitude of the V_∞ vector.

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